Tracing Cosmic Structure Evolution and Testing Cosmological Models with X-ray Galaxy Clusters

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Dark Matter & Dark Energy

- Only 4% of the matter-energy density of the Universe is made of matter we understand
- The unexplained Dark Matter and the Cosmic Reacceleration provide a challenge for fundamental physics ◊ explanations are emerging at every frontier of physics:

  Quintessence (first example – provides nomenclature)

  Theory of gravitation

  Higher dimensions

  String Theory

  Holographic principle

  Interaction of DE and DM ......
- What insights and constraints can observational cosmology provide ?

Overview

- Cosmologies with Dark Energy (described by a simple parametrization of the equation of state of DE)

  and principle of cosmological tests with clusters

- Cosmological tests with nearby clusters

- Cluster abundance as function of z in various cosmologies

- What types of distant clusters need more detailed study

- Requirements for an X-ray observatory to allow these studies

The Observerd Structure in the Universe is influenced by DM and DE

- The expansion dynamics of the Universe

  ◊ determines also the metric: $D_L(z)$, dVol(z), ...

- The density evolution controlles the gravitational growth of fluctuations g(z)

- Interaction or non-intercation effects between the different components are important

  - The nature of Dark Matter determines the form of the fluct. spectrum

  - Dark matter follows the gravitational fluctuation growth

  - Vacuum energy fields do not follow gravitational clumping on small scales

  - interaction of DM and DE ?

The Influence of *w* on Cosmic Evolution

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi}{3} G\rho_x - \frac{kc^2}{a^2} + \tfrac{1}{3}\Lambda c^2 \qquad \frac{\dot{a}^2}{a^2} \equiv H^2 = \frac{8\pi}{3} G \sum \rho_x - \frac{kc^2}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3} G\left(\rho + 3\frac{P}{c^2}\right) + \tfrac{1}{3}\Lambda c^2 \qquad \frac{\ddot{a}}{a} = -\frac{4\pi}{3} G \sum \rho_x (1 + 3w)$$

$$\boxed{\begin{array}{l} w(z) \equiv \rho(z) / P(z) \\ \approx -1 \end{array}}$$

1. **Change of density with expansion**

$$\rho_m \propto a^{-3} \qquad \rho_x \propto a^{-3(1+w)}$$

$$\text{radiation}: \; w = \tfrac{1}{3} \qquad \rho_\gamma \propto a^{-4}$$

$$\Lambda - \text{term}: \; w = -1 \qquad \rho_\Lambda = const.$$

w = w$_0$ + w$_1$*z

$$\rho_m / \rho_x \propto (1+z)^{-3w}$$ small influence of ρ_x in the past

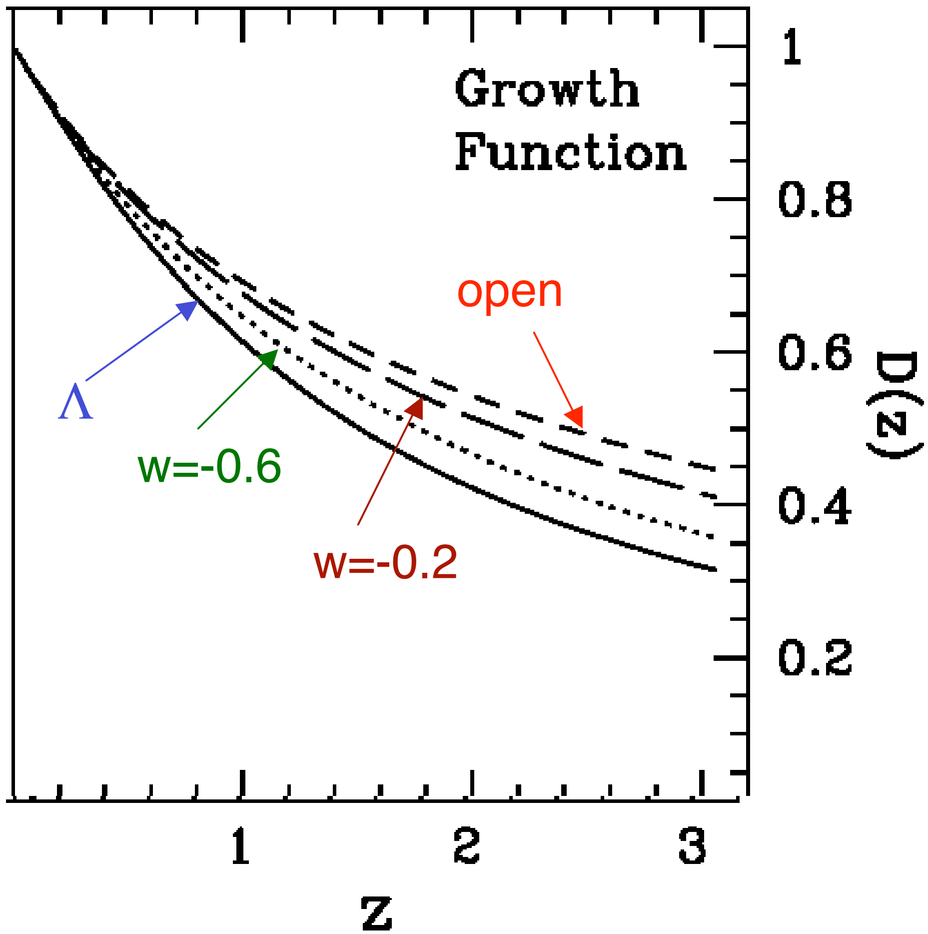
2. **Luminosity distance :**

$$D_L^2(z) \equiv \frac{L}{4\pi \; F} \qquad \zeta(x) = \{\sinh(x), x, \sin(x)\}$$

$$D_L(z) = \frac{c}{H_0} \frac{(1+z)}{|\Omega_R|^{1/2}} \zeta\left\{ |\Omega_R|^{1/2} \int_0^z \left[\sum_i \Omega_i (1+z')^{3(1+w_i)} + \Omega_R (1+z')^2 \right]^{-1/2} dz' \right\}$$

The Influence of *w* on Cosmic Evolution

Density fluctuation growth:



Different Cosmological Tests with Galaxy Clusters and Cluster Populations

1. Galaxy Clusters as Standard Candles (◊ baryon fraction)

2a. G.C. as Tracers of the Evolution of Large-Sacle Structure
(◊ mass function evolution)

2b. Measuring the Large-Scale Structure Matter Distribution
(◊ density fluctuation power spectrum)

3. Using the Depence of Cluster Structure in Detail in Cosmology

Standard Candles

1. **Hubble Diagram: m(z) against z**

$$m_{SN} \propto 5\log D_L(z) + const. \left\{+ \mathrm{K-corr}(z)\right\}$$

$$m_{SN}(z) = f\left(D_L(z), z\right)$$

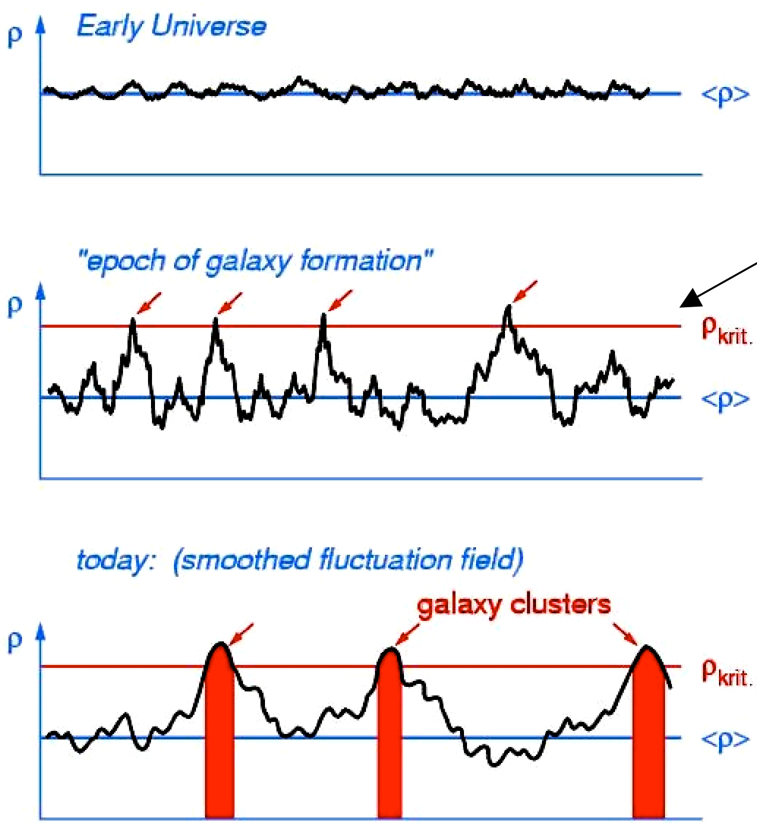
2. **Cluster baryon fraction:**

$$M_{grav} \propto D_\theta = D_L(1+z)^{-2}$$

$$M_{gas} \propto D_\theta^{5/2} \propto D_L^{5/2}(1+z)^{-5}$$

$$\Rightarrow f_b = f(D_L^{3/2}, z)$$

The Ideal Experiment: Cosmic Structure Evolution



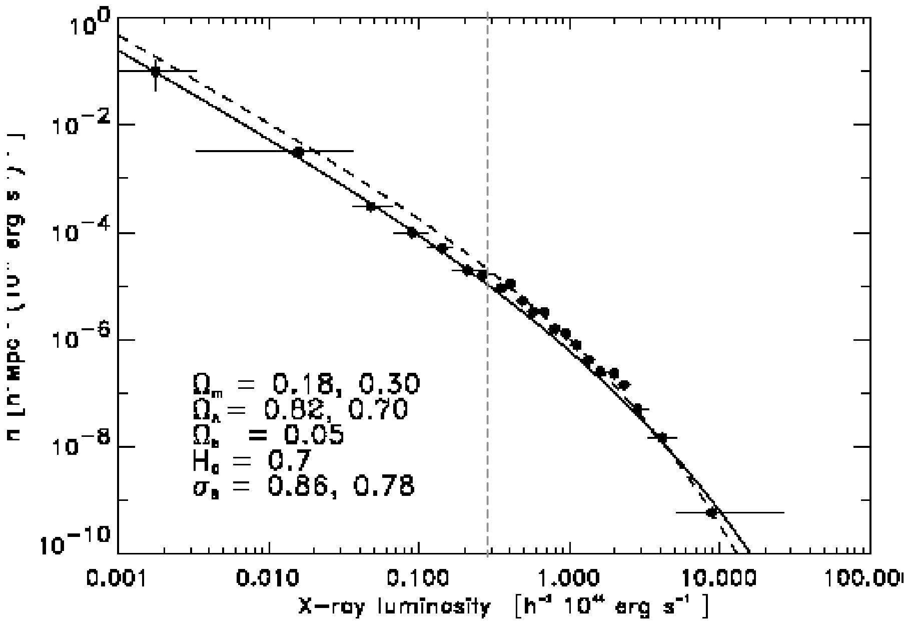
1. **The cosmology determines the growth of the matter density fluctuation amplitude (with time or z) of which the cluster mark the peaks and provide a sensitive statistical measure.**

$$g(z) = f(\Omega_m, \Omega_\Lambda, w_0, w_1)$$

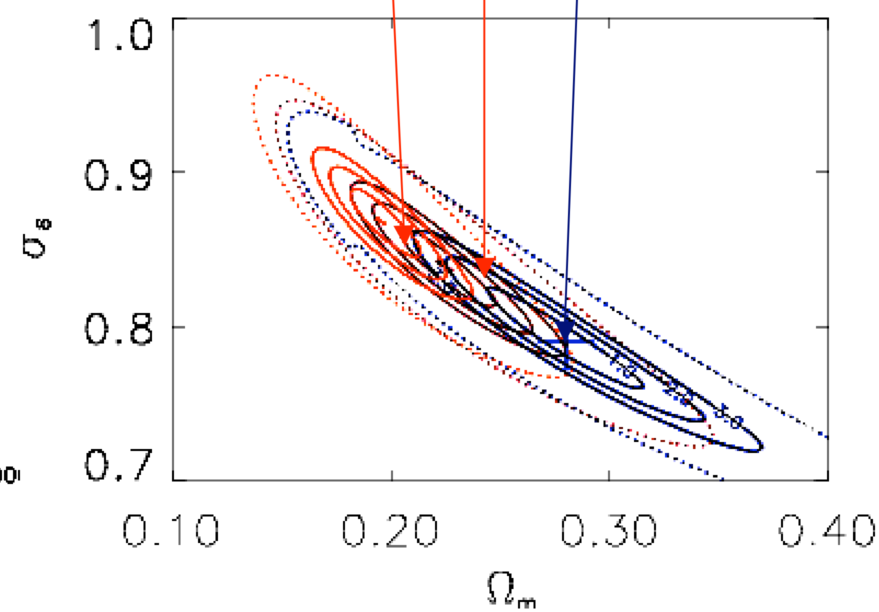
2. **In the observations the number counts as a function of z are observed which also includes the volumina of dz shells – which are cosmology dependent**

$$\frac{dVol(z)}{d\Omega dz} = f(\Omega_m, \Omega_\Lambda, w_0, w_1)$$

Cosmological Constraints from Nearby Cluster X-ray Luminosity Function



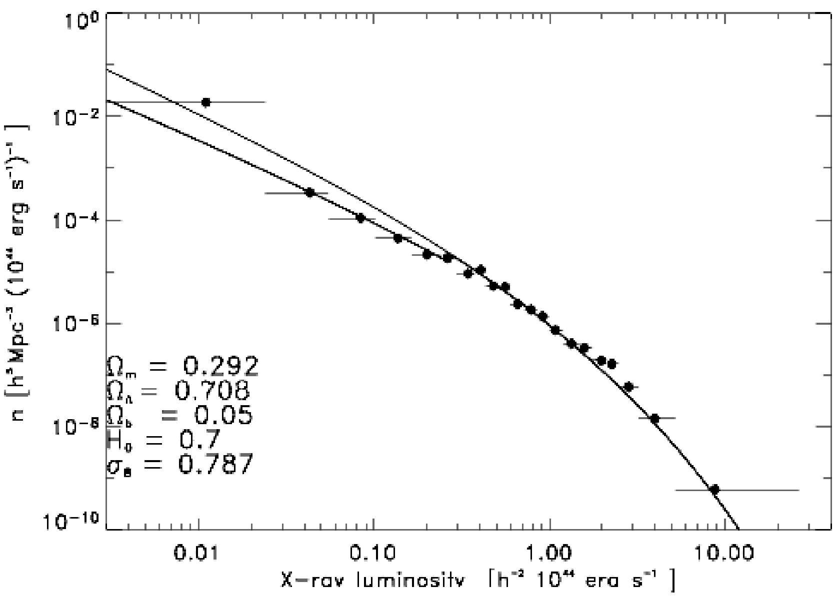
Cut-off Lx= 0.03, 0.1, 0.25 x h^{-1} 10^{44} erg/s

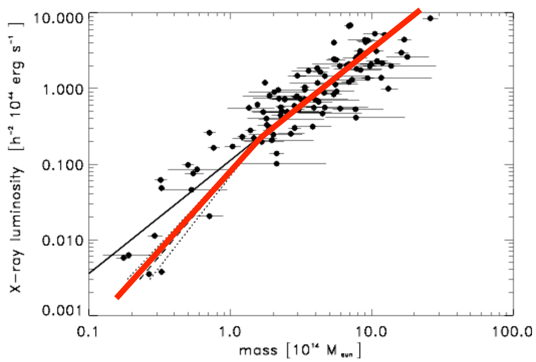


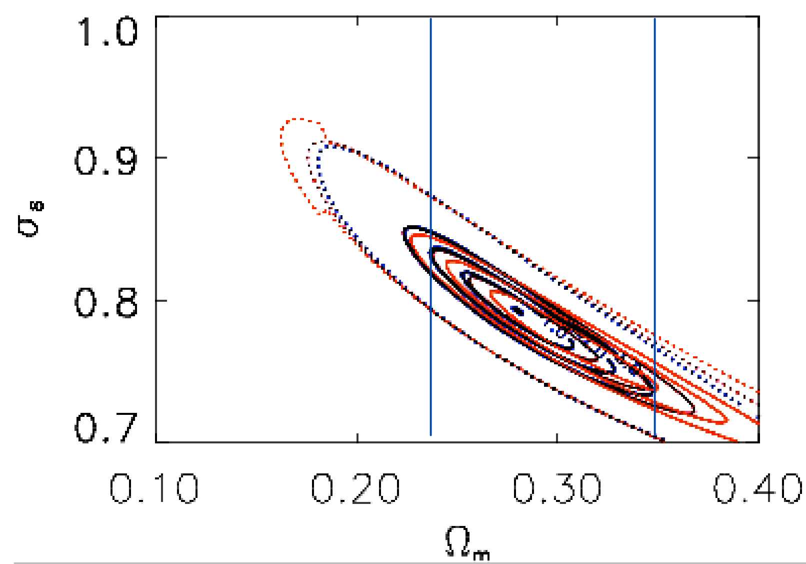
Perfect prediction of the Concordance Cosmological Model for the Luminous Clusters from the REFLEX Sample

Fit with a Broken Power-Law for the M-L Relation

The whole REFLEX data set can be reconciled with the concordance model if we assume a slight change of the M-L relation at small masses:





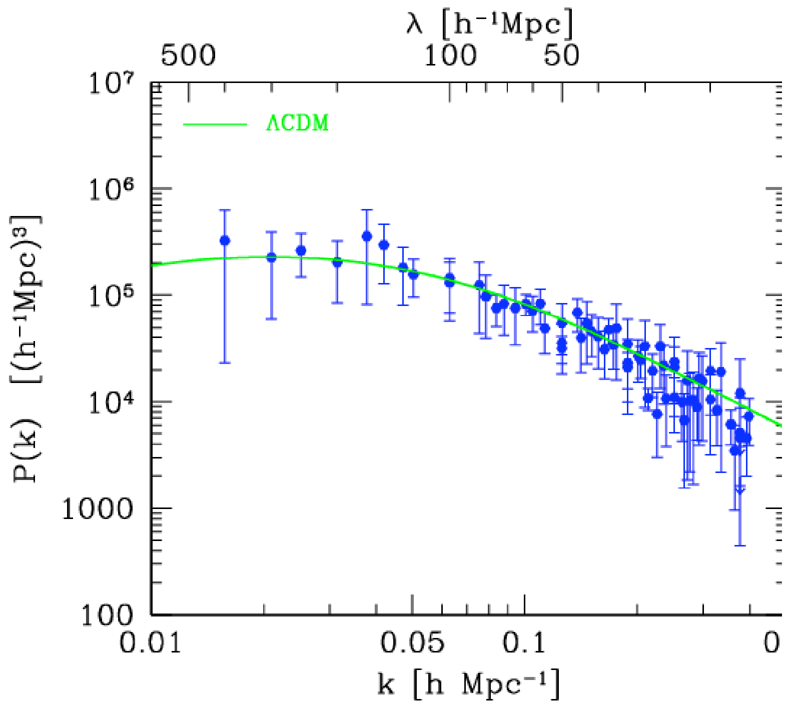


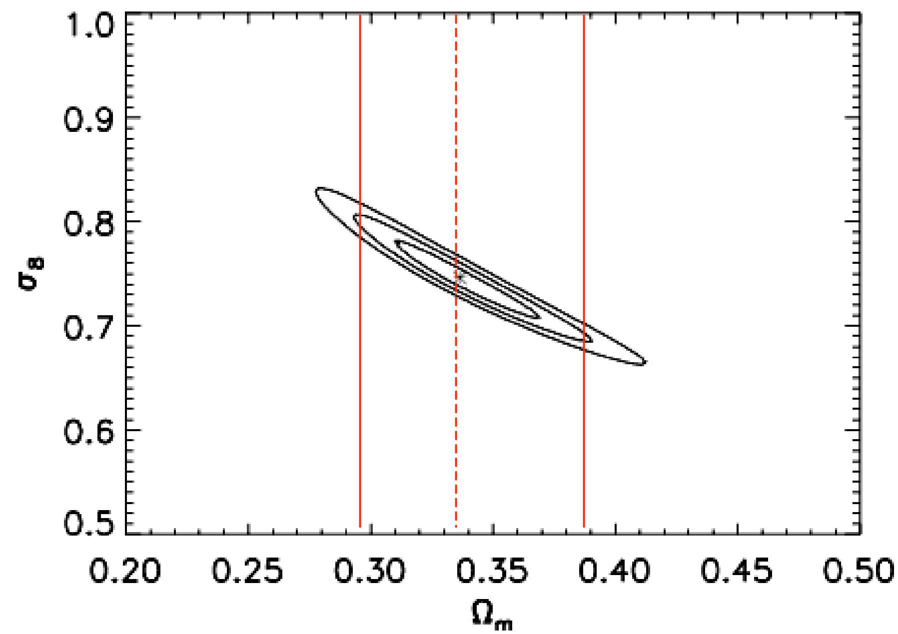
$\Omega_m = 0.235 – 0.350$
(2σ without systematic uncertainties)

Constraints on Cosmological Models and Ω_m from the *REFLEX* Cluster Survey

Combining the REFLEX cluster abundance with the 3dim power spectrum

[Schuecker et al. 2002a,b] (curves are 1,2,3 σ)





Universe with:

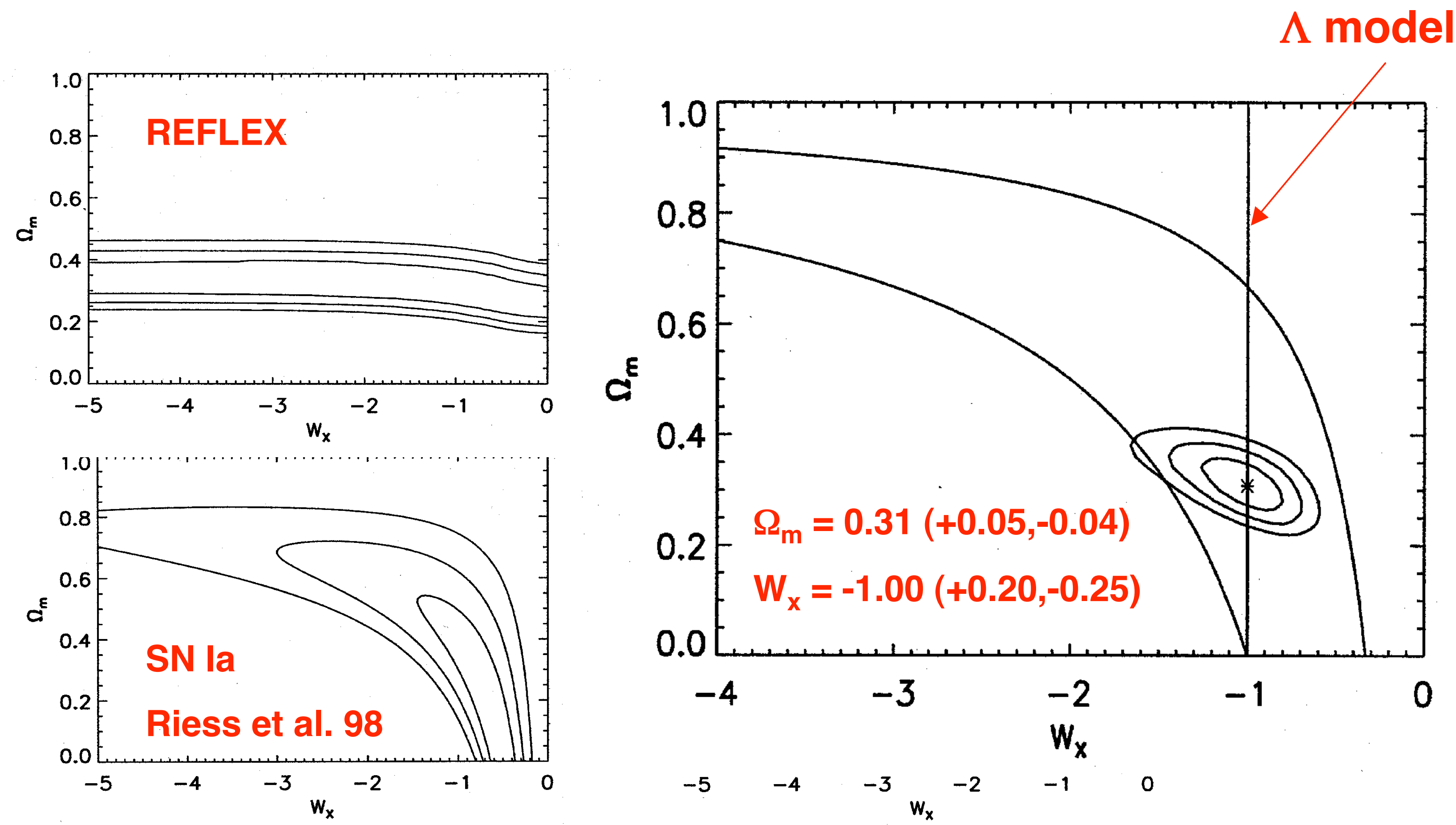
$\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$

◊ $\Delta\Omega_m \sim$ **0.34 +-0.05**
(+ syst. errors +-0.05) **2σ !**

The large-scale distribution and cluster abundance are consistent and can be combined to improve the constraints !

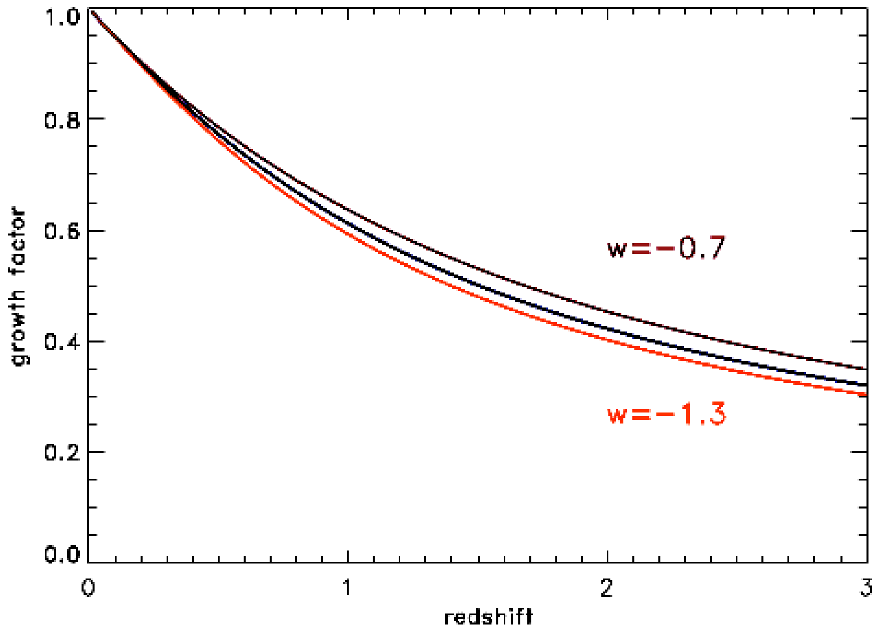
Combined Constraints REFLEX & SN Ia on Ω_m and W_x

Data from REFLEX and SN observations of Riess et al. 1998 and Perlmutter et al. 1999 [Schuecker et al. 2002]

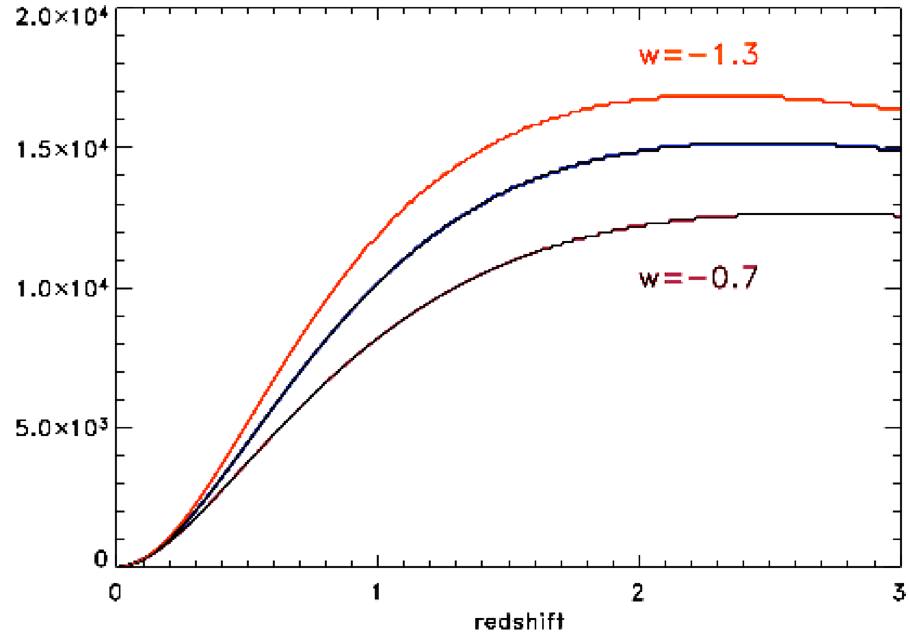


Effects of a constant w-Parameter

growth factor



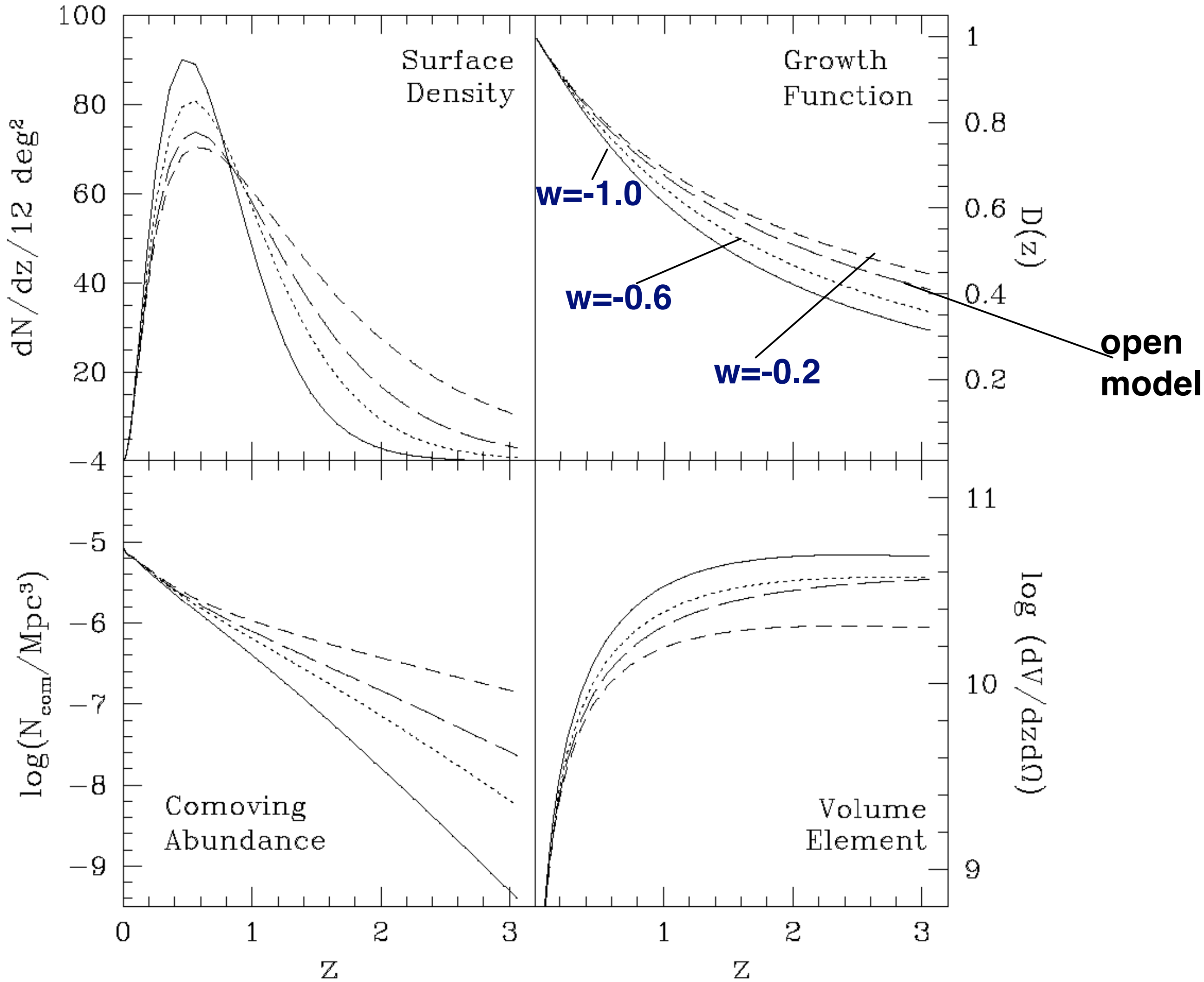
shells of comoving volumes



- **With a larger w , structure evolution proceeds more slowly (a bit similar as for low Ω_m) ◊ more clusters at high redshift !**
- **with a larger w the redshift shell have smaller volumina (this compensates partly the higher g(z) in its increase of the cluster abundance**

$H_0 = 70$ km/s/Mpc
$\Omega_m = 0.3$
$\Omega_\Lambda = 0.7$
$\sigma_8 = 0.79$
$n = 1.0$

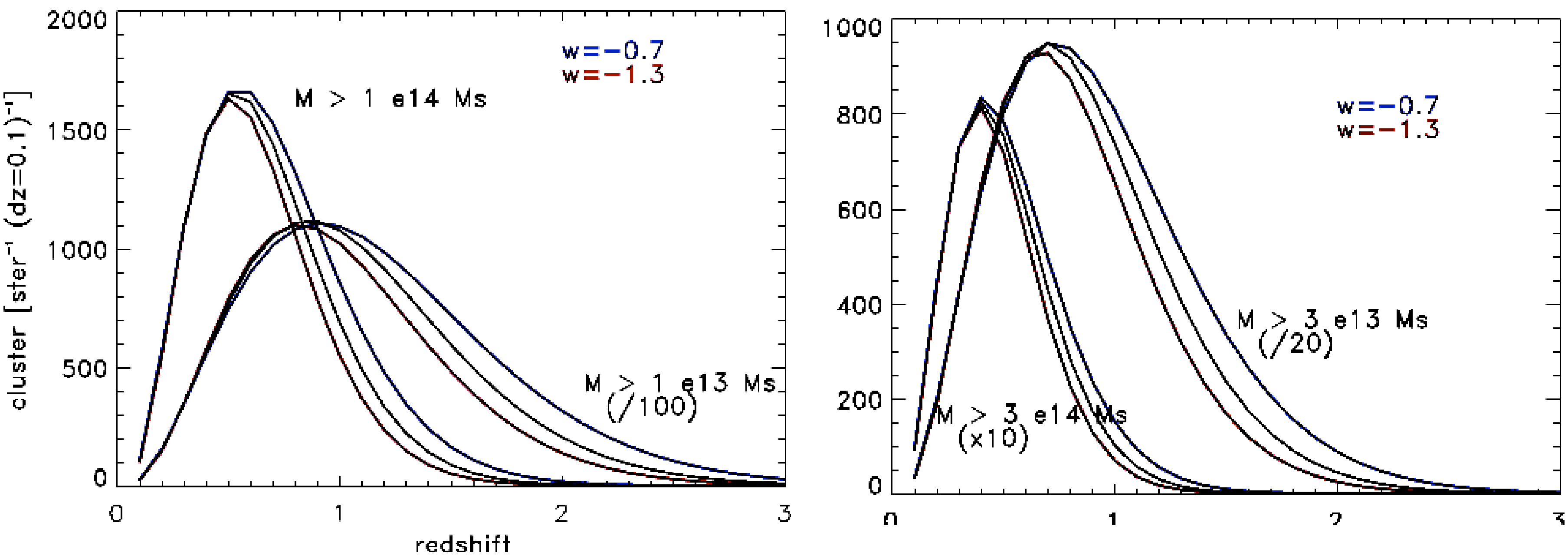
Effect of Changing w = constant



Haiman et al. 2001

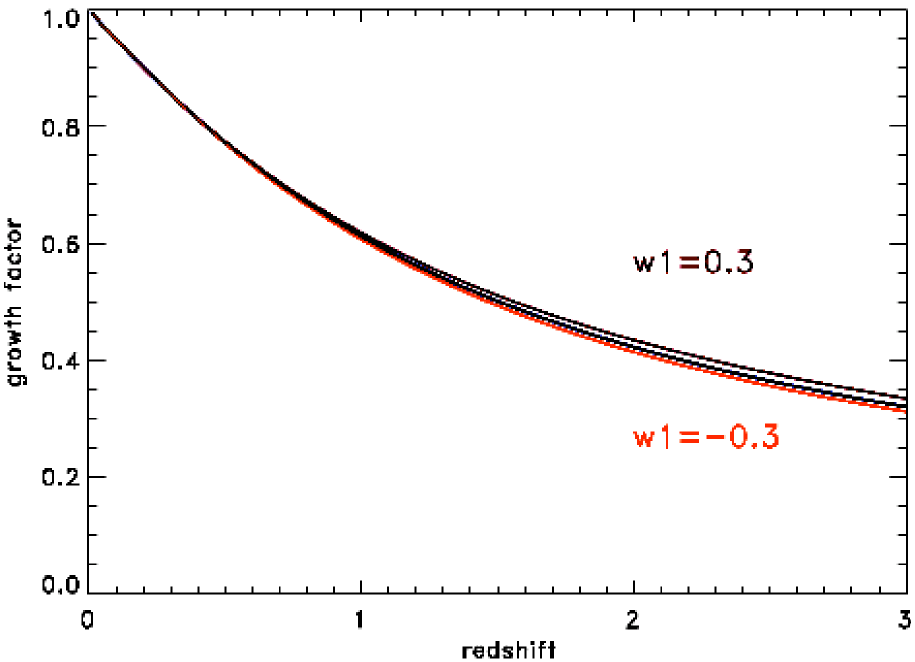
Evolution of the Cluster Mass Function

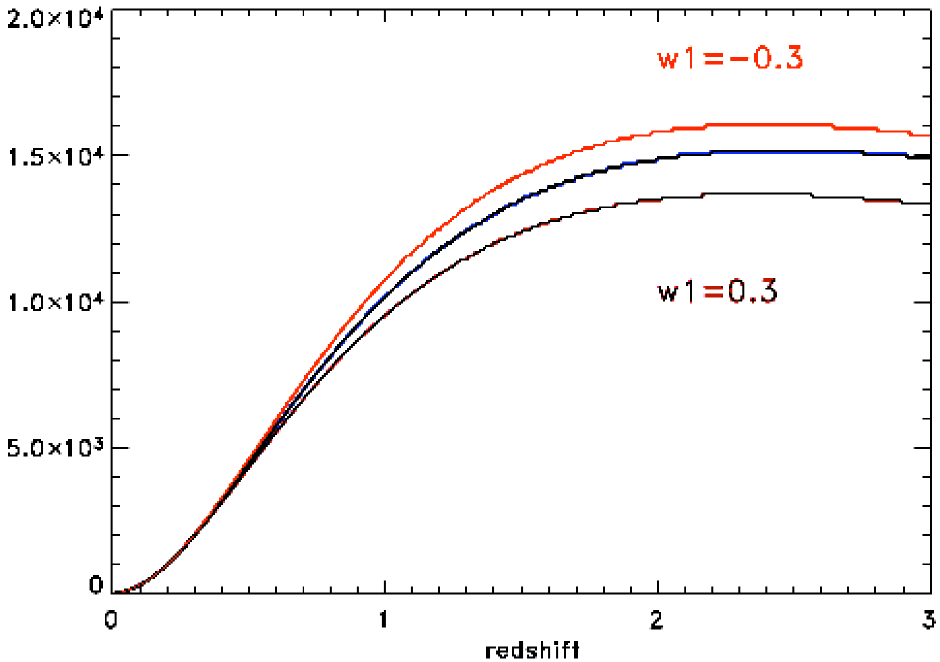
Differential comoving cluster abundance (> Mass$_{limit}$) ster^{-1} dz=0.1^{-1}



◊ **There are more distant clusters for small w !**

Effects of a Changing w(z) Parameter

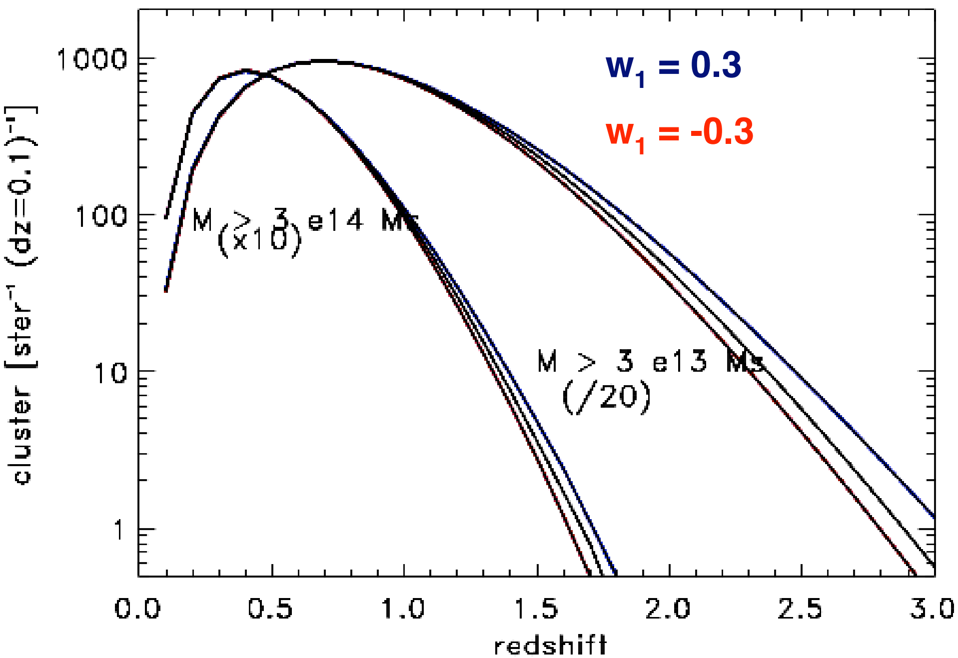


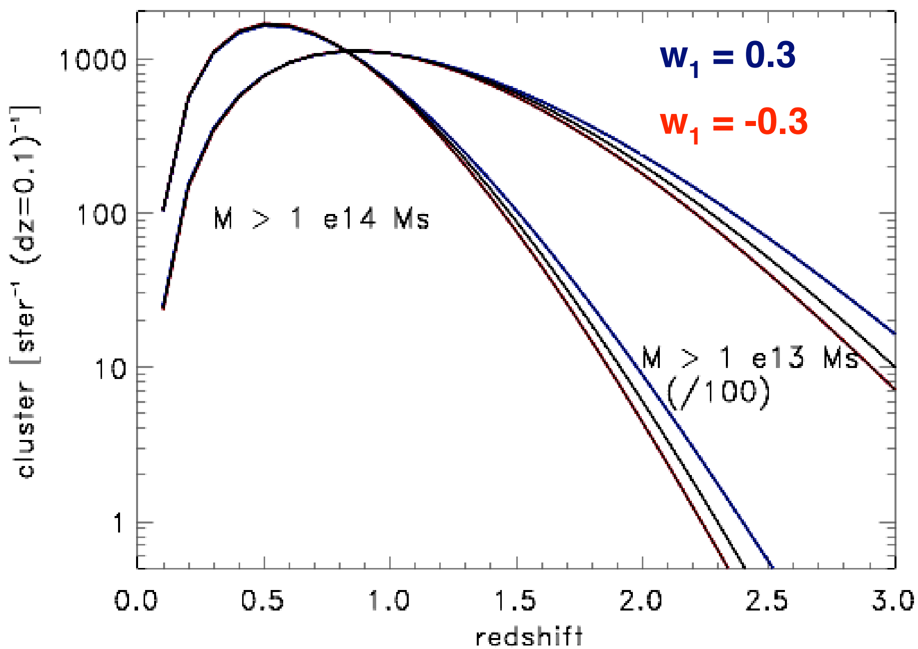


- **Again the model with higher w (positive w1) has more distant clusters per volume element and more of the more massive clusters per redshift shell.**

Evolution of the Cluster Mass Function

Differential comoving cluster abundance (> $Mass_{limit}$) $ster^{-1}$ $dz=0.1^{-1}$





◊There are more distant clusters if w evolves to larger values (smaller negative) values.

◊Measurement will be challenging 30-50% differences in abundance for z >= 2 ---- needs good knowlegde of cluster masses

Possible Constraints on w

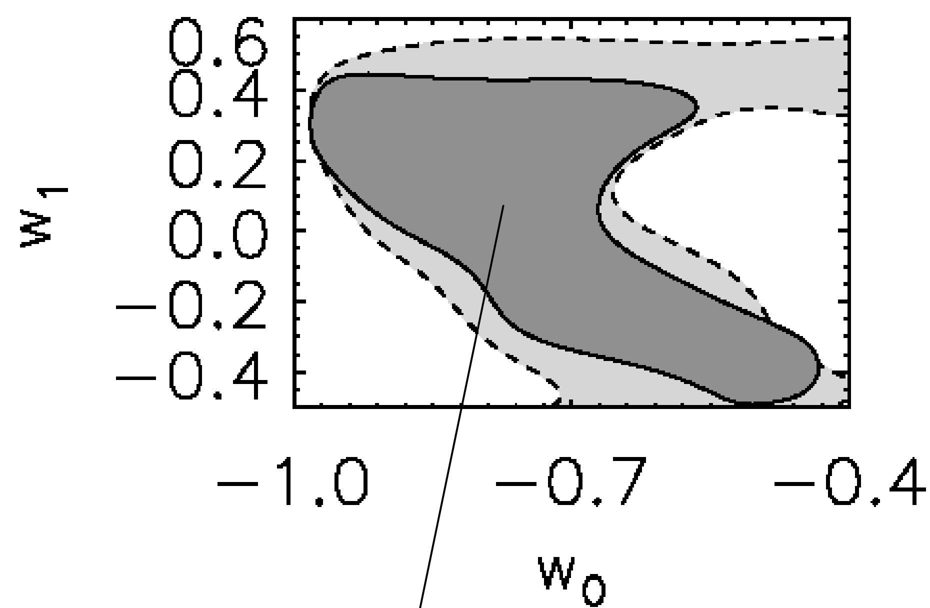
Work by Majumdar & Mohr 2003, 2004 - for DUET, SPT, Planck Surveys (cluster population out to ~ 1.5) :

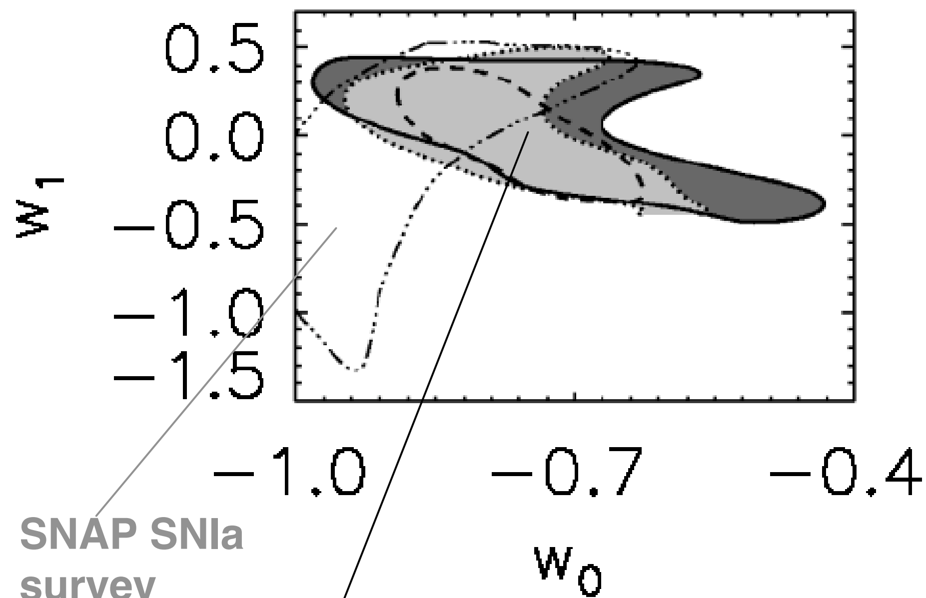
Δw =	**4-5%**	**20-40%**	**10-20%**	**4-6%**
	cluster relations known	rel. unknown	+ P(k)	+P(k) & follow-up

(assuming 30% accuracy in mass observing relations in follow-up studies)

This was ment to be completed in ~ 2010 - now we should aim for a more ambitious goal to probe for time variability of w

Constraints on the w(z) – Parameter
from an SZ survey





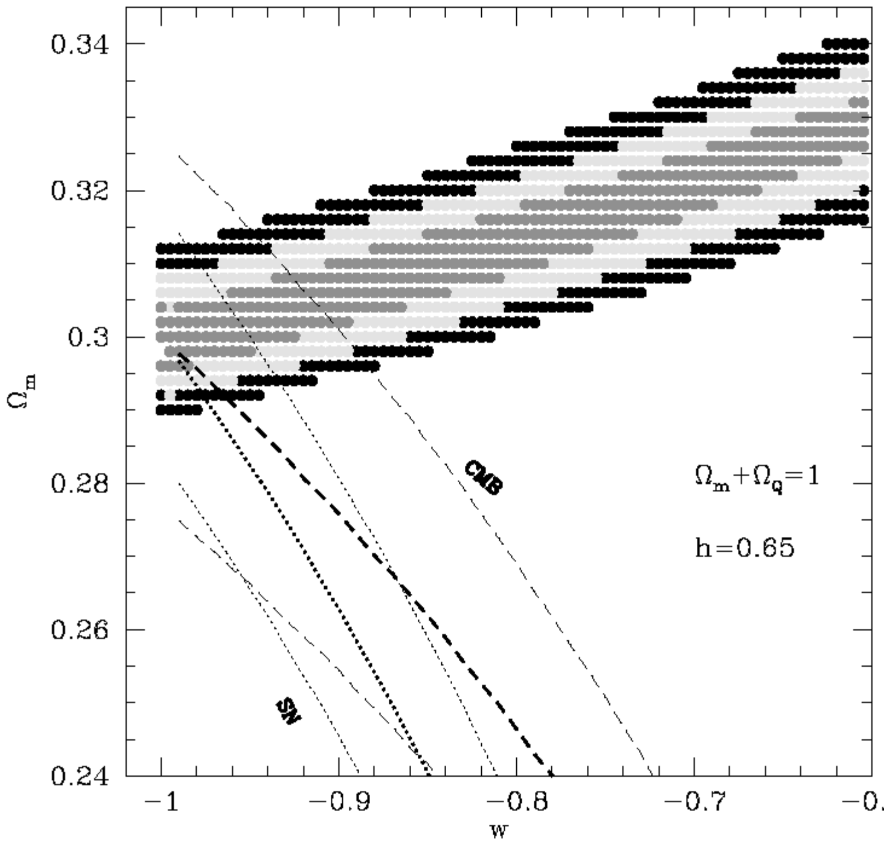
SNAP SNIa survey

~2000 clusters to z~1.5 in 10000 deg^2 M_{lim} ~ 7 10^{14} h^{-1} M_{sun}

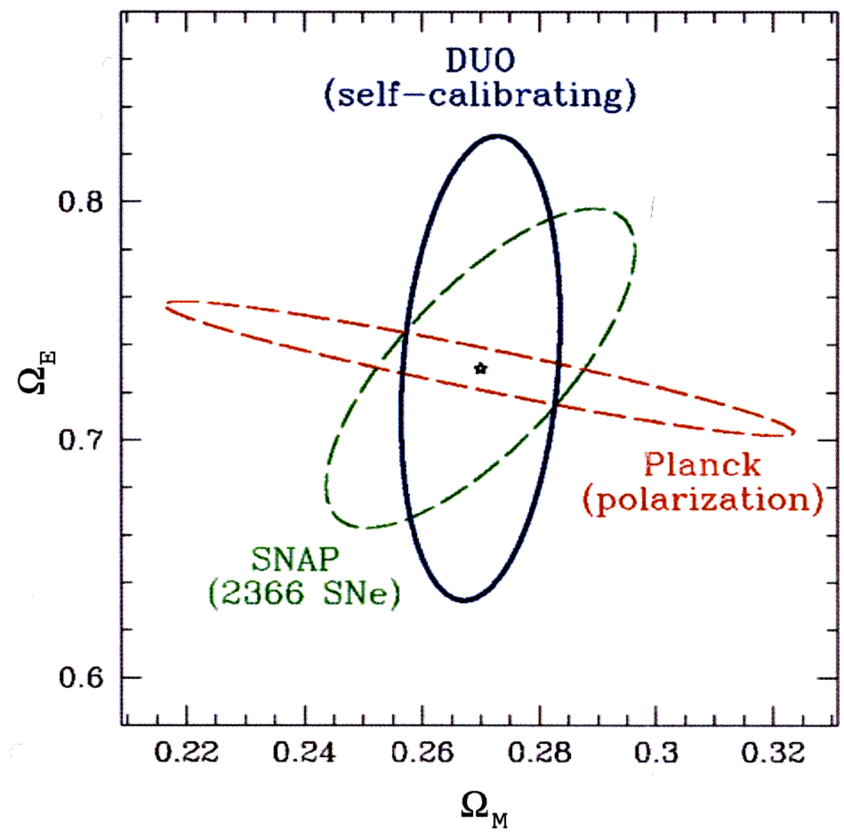
same survey as left and two other surveys to with large depth

Weller et al. 2002 Phys. Rev. Let.

Comparison to other surveys



Haiman et al. 2001



Mohr et al. 2002

Tests involving the study of the growth of large-scale structure (tests of the dynamics of gravitational instabilities) provides constraints complementary to the geometry and CMB studies.

How many Test Objects Do We Find ?

Redshift	mass	clusters /100 deg2	X-ray luminosity
$z > 2$	$> 10^{14}\ M_{sun}$	0.5	10^{44} erg/s
	$> 3\ 10^{13}\ M_{sun}$	100	$1.5\ 10^{43}$ erg/s
	$> 10^{13}\ M_{sun}$	2000	$3\text{-}4\ 10^{42}$ erg/s
$z > 2.5$	$> 3\ 10^{13}\ M_{sun}$	15	$2\ 10^{43}$ erg/s
	$> 10^{13}\ M_{sun}$	600	$3\text{-}5\ 10^{42}$ erg/s
$z > 3$	$> 3\ 10^{13}\ M_{sun}$	1	$2.7\ 10^{43}$ erg/s
	$> 10^{13}\ M_{sun}$	100	$4\text{-}6\ 10^{42}$ erg/s

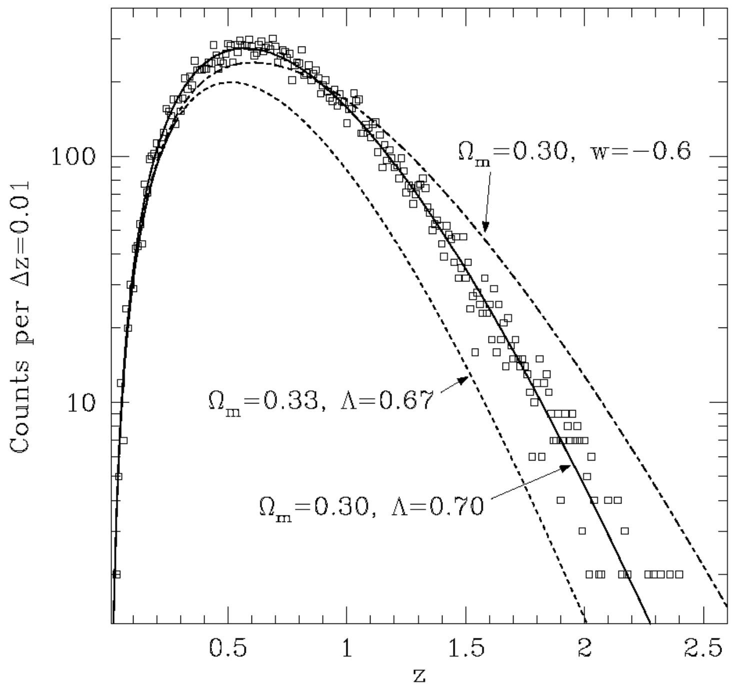
Requirements for Cosmological Studies

1. To find a sufficiently large sample of distant clusters we have to rely on systematic X-ray and SZ surveys
   - XMM archive and DUO type survey will provide 100s of clusters at z = 1 .. 1.5 -- mission like DUET or better will bring us to z ~ 2
   - planned SZ surveys are very promising for the finding of distant clusters due to the non-dimming surface brightness
2. We need to know the structural properties and masses of the clusters found by other means very precisely (~ as precisely as we know the present day cluster properties)

◊ The latter is the challenge for ConX/XEUS: precise cluster characterization at z ~ 2

Can we Really Find Distant Clusters ?

1.



Expected cluster counts in the 4000 deg^2 SZ survey with the South Pole Telescope

[Ruhl et al. 2004 astro-ph/0411122]

2. **Redshift record breaking luminous X-ray cluster found in the XMM archive by MPE-ESO-AIP collaboration ◊ Announcement by Chris Mullis et al. on 2. 3. 2005 in Kona !**

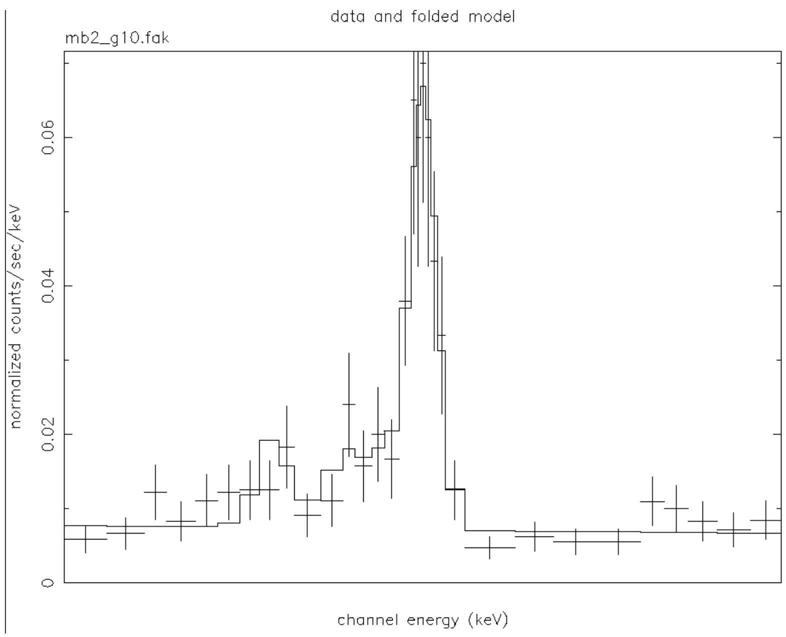
Task for ConX-XEUS

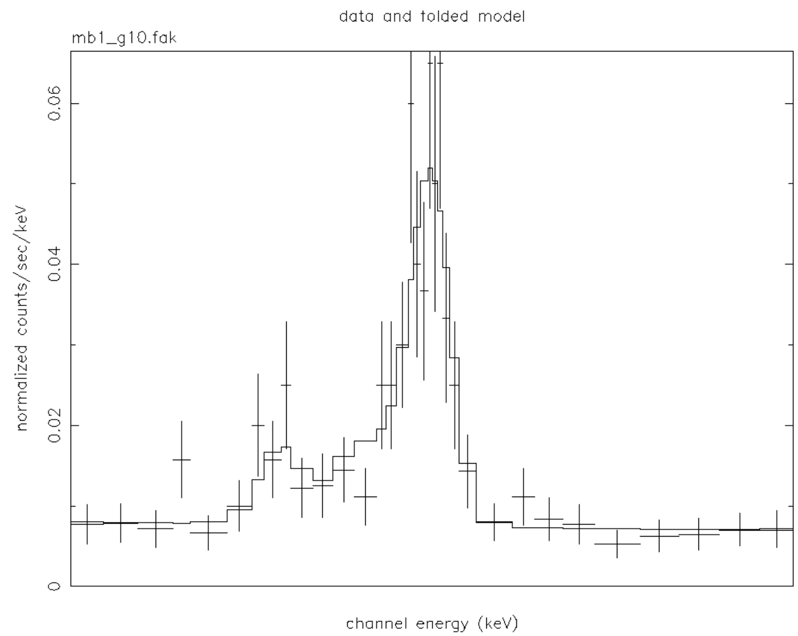
To best characterize :

- **abundant clusters at $z \sim 2$ with $M \sim 3\ 10^{13}\ h^{-1}\ M_{sun}$**
- **more rare clusters „ $M \sim 10^{14}\ h^{-1}\ M_{sun}$**

Spectroscopy as Temperature and Structure Diagnostics

Fe-line in the Coma Cluster ICM in a simulated ASTROE-2 observation of 80 ksec for 100 and 300 km/s turbulence

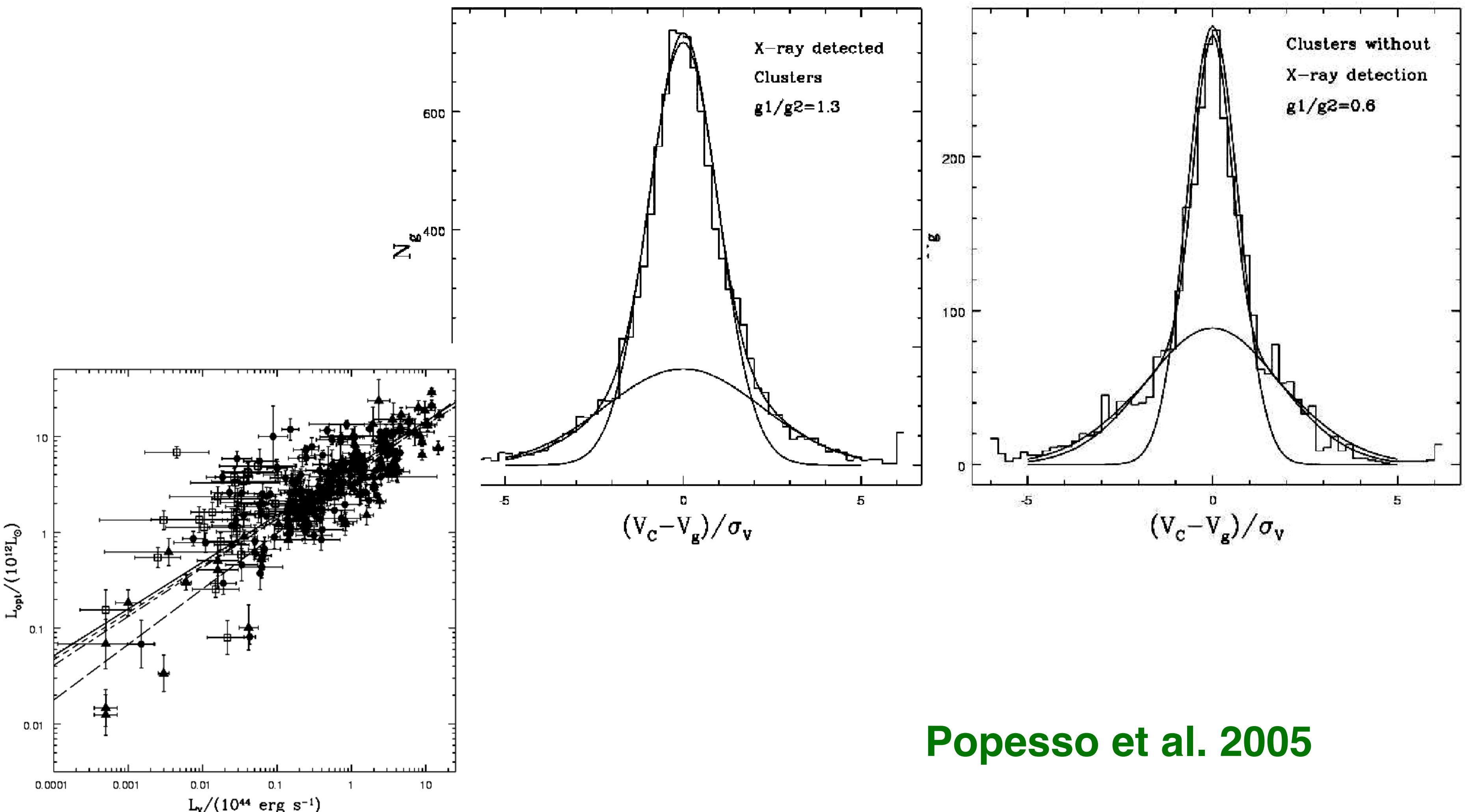




3-fold way of temperature determination:

1. Spectral fits, 2. Line ratios, 3. Line width

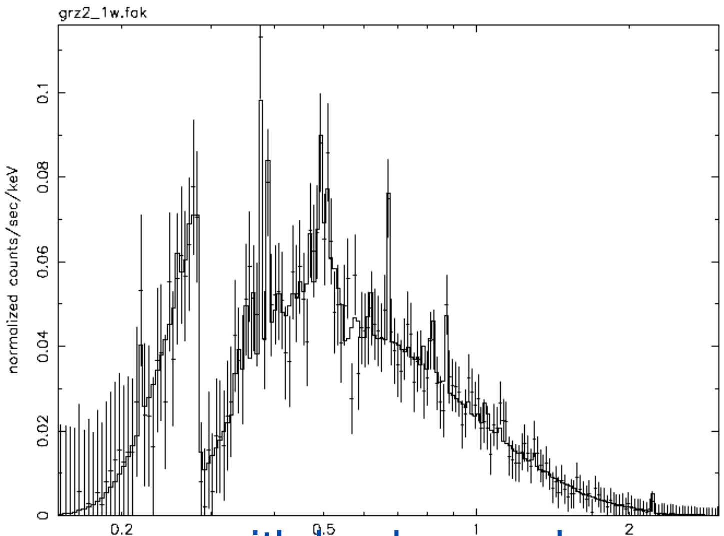
Structure Discrimination Learned from X-ray/SDSS Comparison for Nearby Clusters



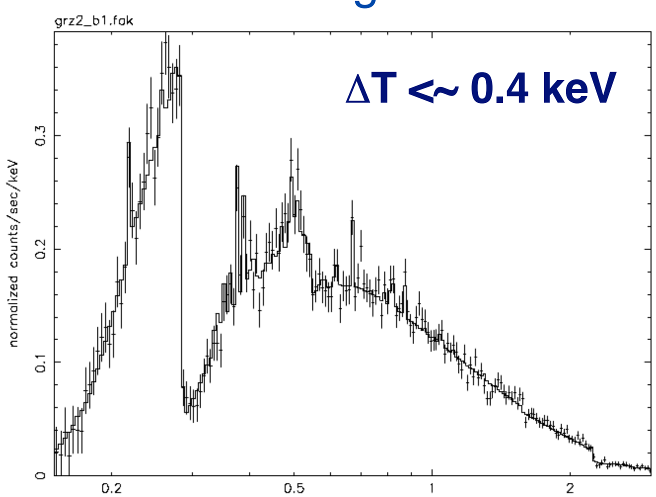
Popesso et al. 2005

Spectra of a 3 10^{13} M_{sun} Group at z ~ 2

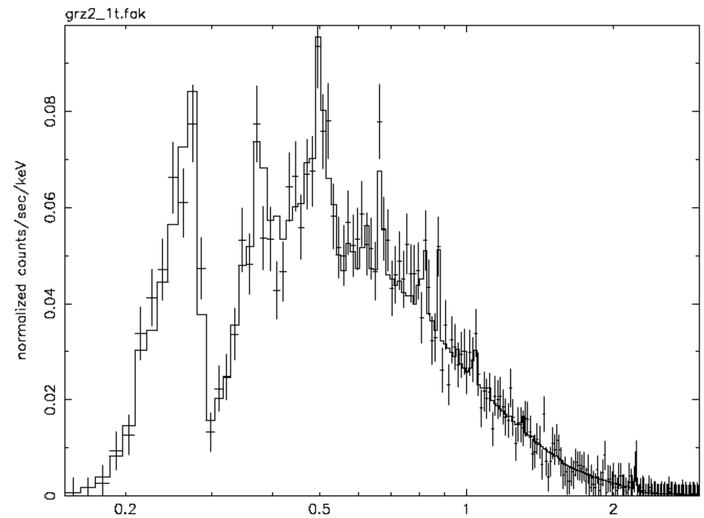
XEUS STJ



with background



XEUS TES



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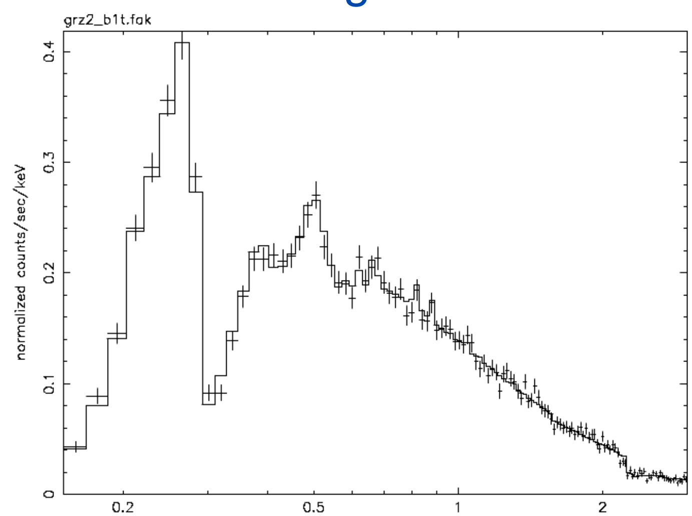
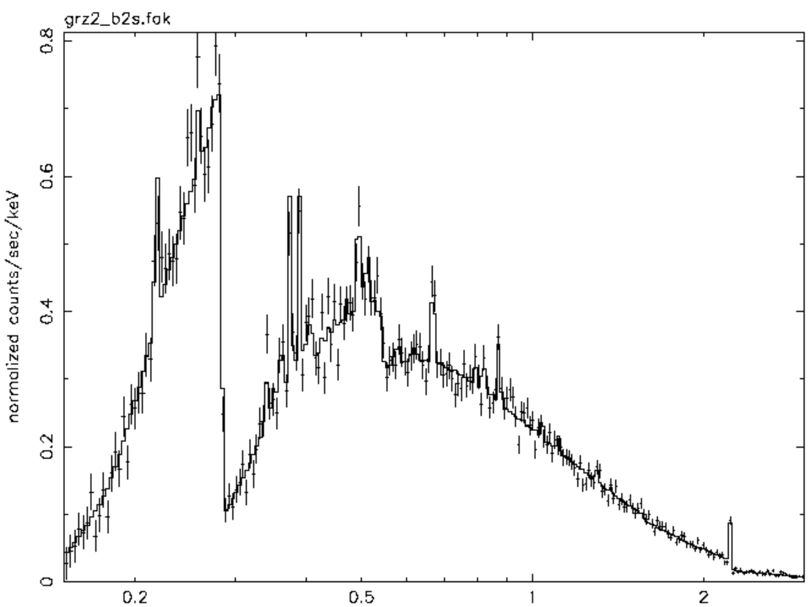
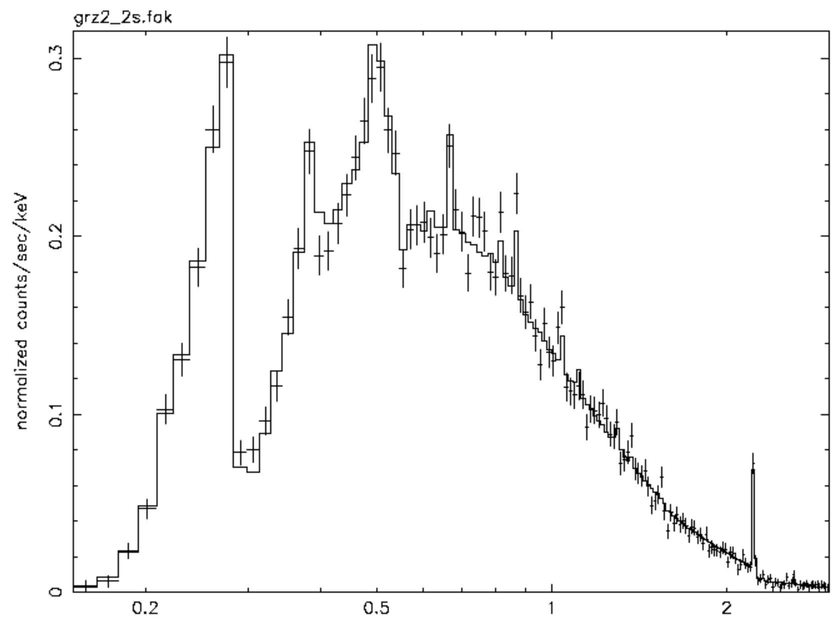


Spectra of a z ~ 2 Cluster (M ~ 10^{14} M_{sun})

100 ks observation with STJ
incl. sky background



100 ks observation with TES
no sky background



Temperature measurement to better than ΔT = 0.1 keV

Conclusions

1. **XEUS is well fit to provide a good characterization of galaxy clusters out to z >~ 2 even so the very massive and luminous clusters are not any more found at these redshifts**

   By pushing the limits t z~2 we get a larger leverage to look for the time variation of w

   All cosmological tests needed to break degeneracies in Ω_m, Ω_Λ, w_0, w_1, + ...

1. **These clusters are not only interesting as probes of cosmology and structure growth but also as laboratories for the evolution of the intergalactic medium and the galaxy population ◊ talks by Arnaud, Mushotzky, Kaastra !**

   Thus such distant cluster observations will serve several very important purposes (with same observations requirements)

Requirements

1. High collecting power – at least current XEUS effective area   ~ $10 m^2$
2. Most crucial: low back ground – instrumental and partical background have to be less than the X-ray sky background (as for ROSAT PSPC) !!!
3. Sufficient field-of-view   > 5 arcmin for very distant clusters ~10 arcmin for redshift range z= 0.5 – 1
4. Reasonable angular resolution: 2-4 arcsec
5. Good spectral resolution: 3 eV or better